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Cosmic Microwave Background Anisotropy with Late Time Entropy Production*

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Abstract

We discuss effects of cosmological moduli fields on the cosmic microwave background (CMB). If a modulus field ϕ once dominates the universe, the CMB we observe today is from the decay of ϕ and its anisotropy is affected by the primordial fluctuation in the amplitude of the modulus field. As a result, constraints on the inflaton potential from the CMB anisotropy can be relaxed. In addition, with the cosmological moduli fields, *correlated* mixture of adiabatic and isocurvature fluctuations may be generated, which results in enhanced CMB angular power spectrum at higher multipoles relative to that of lower ones. Such an enhancement can be an evidence of late time entropy production due to the cosmological moduli fields, and may be observed at on-going and future experiments.

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1 Introduction

In superstring theory [1], it is well known that there are various flat directions parameterized by scalar fields. (Hereafter, we call these fields as “moduli” fields.) Since their potential is usually generated by effects of supersymmetry (SUSY) breaking, their masses are expected to be of the order of the gravitino mass. Although masses of the moduli fields can be as light as (or even lighter than) the electroweak scale, moduli fields do not affect collider experiments since their interactions are suppressed by inverse powers of the gravitational scale.

Cosmologically, however, they may cause serious problems [2]. If the mass of the moduli fields $m_\phi \lesssim O(10 \text{ TeV})$, reheating temperature of the universe becomes lower than $\sim 1 \text{ MeV}$. With such a low reheating temperature, the success of the standard big-bang nucleosynthesis (BBN) is spoiled. For lighter moduli fields ($m_\phi \lesssim O(100 \text{ MeV})$), they survive until today and overclose the universe. One solution to these difficulties is to push up the mass of the moduli fields [3]. In particular, in Ref. [4], it was pointed out that the scenario with heavy moduli can naturally fit into the framework of the anomaly-mediated SUSY breaking [5]. Indeed the reheating temperature can be higher than $\sim 1 \text{ MeV}$ if $m_\phi \gtrsim O(10 \text{ TeV})$. In this case, the BBN occurs after the decay of the modulus field. Although the thermal history after the BBN is mostly the same as the standard one, cosmology before the modulus decay is completely different. Importantly, fluctuations of moduli fields affect the cosmic microwave background (CMB). In this talk, we consider this scenario and study its consequence in the CMB.

2 Effects of moduli fields on CMB

Now we discuss the CMB angular power spectrum from the scenario with the cosmological modulus field [6]. First, we emphasize that there are two independent sources of the CMB anisotropy, i.e., primordial metric perturbation Ψ_i induced by inflaton field fluctuation and amplitude fluctuation of the modulus field $\delta\phi_i$ which is of order $H_{\text{inf}}/2\pi$ where H_{inf} is the Hubble parameter during inflation. Therefore, the resultant CMB angular power spectrum C_l is given in the following form:

$$C_l = C_l^{(\text{adi})} + C_l^{(\delta\phi)}. \quad (1)$$

Here, $C_l^{(\text{adi})}$ is from the perturbation in the inflaton field, which is of order Ψ_i^2 . On the contrary, $C_l^{(\delta\phi)}$ is from the primordial fluctuation of the modulus amplitude, which is of order $\delta\phi_i^2$. (Notice that there is no term which is of order $\Psi_i\delta\phi_i$ since two fluctuations are uncorrelated.) $C_l^{(\text{adi})}$ can be calculated by following the standard method. In calculating $C_l^{(\delta\phi)}$, we must specify the origin of CDM and baryon. Here, we assume that CDM is generated by the decay of ϕ . In this case, after the decay of the modulus field, there is no entropy between CDM and radiation. On the contrary, we consider two possibilities of generating baryon asymmetry: (i) the baryon asymmetry is (somehow) generated at the

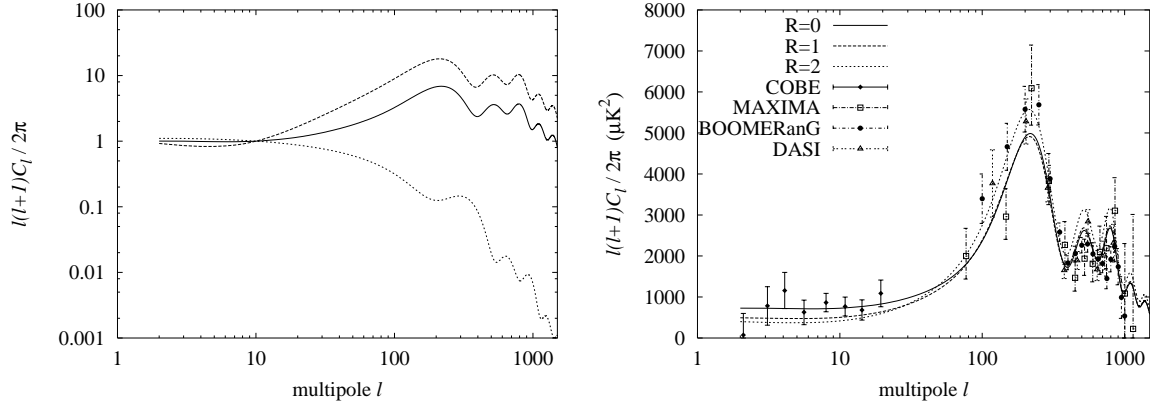


Figure 1: *Left*: The CMB angular power spectrum $C_l^{(\delta\phi)}$ for the case with the correlated isocurvature perturbation in the baryonic sector (dashed line), as well as C_l for purely adiabatic (solid line) and purely baryonic isocurvature (dotted line) cases. We used the normalization $[l(l+1)C_l/2\pi]_{l=10} = 1$. *Right*: The CMB angular power spectrum C_l for $R = 0$ (solid), $R = 1$ (dashed), and $R = 2$ (dotted) where $R \equiv S_i/\Psi^{(\text{adi})}$. The overall normalization of C_l is determined to be best fitted to the the observational data [9]. In these figures, the cosmological parameters are taken such that $h = 0.65$, $\Omega_b h^2 = 0.019$, $\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$, and scale-invariance is assumed both for Ψ_i and S_i .

time of (or after) the decay of ϕ , or (ii) the Affleck-Dine (AD) mechanism [7] generates the baryon number.

Let us first consider the case (i). In this case, there is no entropy between baryon and radiation, so the cosmic fluctuations are same as the conventional adiabatic case once the modulus field decays. Thus, if we neglect the scale dependences of Ψ_i and $\delta\phi_i$, $C_l^{(\delta\phi)}$ is proportional to $C_l^{(\text{adi})}$. In this case, the CMB angular power spectrum is the same as the usual adiabatic case if the normalization of the initial fluctuations are properly chosen. However, this fact has significant implications when we construct a model of inflation. First of all, since curvature perturbation induced by the modulus field $\Psi^{(\delta\phi)}$ is of order $H_{\text{inf}}/\bar{\phi}_i$ where $\bar{\phi}_i$ is the initial amplitude of ϕ , large cosmic perturbation can be generated by lowering $\bar{\phi}_i$ even if H_{inf} is small. Furthermore, usually, scale dependence of $\delta\phi_i$ is milder than that of Ψ_i . Thus, when $C_l^{(\text{adi})} \ll C_l^{(\delta\phi)}$ is realized, the resultant CMB angular power spectrum may be like that from the scale-invariant adiabatic perturbation even if Ψ_i has a strong scale dependence. These facts relax constraints on the potential of the inflaton field [6, 8].

Next we consider the case (ii). Here we assume that the initial value of the fluctuation in the AD field is negligibly small.^{#1} Even when there is no primordial fluctuation in the AD field, however, non-vanishing isocurvature fluctuation is generated in the baryonic

^{#1}This may happen when, for example, the effective mass of the AD field is comparable to H_{inf} during the inflation.

sector if $\delta\phi_i \neq 0$. Since, initially, there is no fluctuation in the baryon energy density, the entropy between baryon and ϕ exists; $S_{b\phi} \equiv \delta_b - \delta_\phi = S_i \neq 0$, where $\delta_x \equiv \delta\rho_x/\rho_x$. This entropy is conserved until the modulus field decays, and it becomes the entropy between photon and baryon after the decay of ϕ . Therefore, in calculating $C_l^{(\delta\phi)}$ which is generated by the primordial fluctuation in the modulus amplitude, initial condition for the baryonic density fluctuation is different from the conventional adiabatic one, and is given by, in deep radiation dominated epoch [6],

$$\delta_b = S_i + (3/4)\delta_\gamma = 4.5\Psi^{(\delta\phi)} + (3/4)\delta_\gamma. \quad (2)$$

Importantly, the curvature perturbation $\Psi^{(\delta\phi)}$ is induced by the initial entropy perturbation S_i . In addition, notice that the first term in the right-handed side of the above equation does not exist in the usual adiabatic ones. Initial conditions for other perturbations are the same as the usual adiabatic case. The first term in Eq. (2) gives rise to the non-vanishing entropy in the baryonic sector and hence we call it as the “isocurvature” term. Here, it should be emphasized that such an isocurvature fluctuation is *correlated* with the contribution from $\Psi^{(\delta\phi)}$ which gives rise to the effect like the conventional adiabatic fluctuation. Thus, the effect of this “isocurvature” fluctuation is completely different from the conventional *uncorrelated* isocurvature fluctuation.

In Fig. 1, we show the total CMB angular power spectrum with such a correlated isocurvature fluctuation in the baryonic density fluctuation. Since there are two sources of the cosmic perturbations, Ψ_i and S_i (or equivalently, $\delta\phi_i$), we define $R \equiv S_i/\Psi^{(\text{adi})}$, where $\Psi^{(\text{adi})}$ is the gravitational potential in the adiabatic mode at the radiation dominated epoch after the modulus decay. (For simplicity, we neglect the scale dependence of R .) Treating R as a free parameter, we plot the total C_l for several values of R in Fig. 1. As one can see, correlated isocurvature perturbation in the baryonic sector may result in an enhancement of C_l at higher multipoles relative to that at lower ones. Therefore, on-going and future experiments will give us interesting tests of the scenario with the cosmological moduli fields.

3 Conclusion

We have studied the effects of the cosmological moduli fields on the CMB anisotropy. In the scenario with the cosmological moduli fields, *correlated* isocurvature fluctuation may exist in the baryonic sector which results in enhanced CMB angular power spectrum at higher multipoles relative to that at lower ones. In addition, even in the case where there is no isocurvature perturbation, the cosmological modulus field may have important implication to the model-building of the inflation.

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